1970

Color appearance prediction equations for daylight to tungsten illumination changes

Daniel James Gallagher
Lehigh University

COLOR APPEARANCE PREDICTION EQUATIONS FOR DAYLIGHT TO TUNGSTEN ILLUMINATION CHANGES

by

DANIEL JAMES GALLAGHER

A THESIS

Presented to the Graduate Committee of

Lehigh University

in Candidacy for the Degree of

Master of Science

in

Psychology

Lehigh University

1970

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Arts.

April 20, 1970

Francis J. Nield
Professor in charge

Francis J. Nield
Chairman of the Department

ACKNOWLEDGMENTS

The author would like to thank Dr. Wuest, who served as professor in charge of this thesis, Dr. Allen, who directed and inspired this research, and Drs. Mankin and Shortess, who advised and helped refine the final presentation.

The author would also like to thank Mr. Lou Manara, of American Cyanamid, Bound Brook, N. J. for technical assistance, and Miss Josephine Lewinski, who prepared the dyings.

The author is extremely grateful to the professional colormatchers who served as observers in this experiment:

Sam Evans, Magee Carpet, Bloomsburg, Pa.

Victor Collen, Collins and Aikman, Pen Argyl, Pa.

Howard Schellhorn, Philadelphia Dye Works, Philadelphia, Pa.

Joe Orlando, American Cyanamid, Bound Brook, N. J.

William Mangold, Anchor Thread, Groveville, N. J.

Dan Sassi, Davidson and Hemmindinger, Easton, Pa.

Wilmer DeEsch, Blue Ridge Winkler Textile, Bangor, Pa.

TABLE OF CONTENTS

ABSTRACT

Predictive equations have been developed that describe apparent color change when illumination is changed from daylight to tungsten. The methodology of the present study reflects standard industrial laboratory practice to the fullest extent possible, employing professional colormatchers as observers, using dyed carpet materials as stimuli, and employing the Macbeth illumination booth for the light sources. Prediction equations are generated from the mathematical method proposed by Brewer (1954). These new predictions are shown to agree with the formulations of Judd, Helson and Warren (1952). The pattern of disagreement with other studies (Burnham, Evans and Newhall, 1952, 1957) indicate that their use of differential adaptation of left and right eyes may be the major reason for the differences that can be noted between the present predictions, the Judd-Helson predictions, and the Burnham, Evans and Newhall predictions.

INTRODUCTION

In recent years, several attempts have been made to specify the change in color appearance that occurs when illumination is changed (Helson, Judd and Warren, 1952; Burnham, Newhall and Evans, 1952, 1957). These experimental attempts have generally presented a set of equations that transform the X, Y, and Z tristimulus values of a color under one illuminant to X', Y', and Z' tristimulus values under a second illuminant. Although such transformations are used as a summary of the experimental results, they may also be used to predict tristimulus values of a color under a second source if the tristimulus specifications are known for the color under the first illuminant. Such predictions could be useful to an industrial colormatcher. He would be able to determine how to formulate a color that would remain the same under the two illuminant conditions.

However, the results from the previous research attempts have not been adopted for empirical prediction at the industrial level. One reason for this is that the various equations predict different tristimulus values. The colormatcher does not know which set of transformations to choose. A second reason is less obvious, but more important. Each set of predictive equations has been derived from data gathered under conditions that are far removed from the colormatcher's world. The experimental conditions have usually been artificial, and have not produced predictions that agreed well with the colormatcher's observations.

The intent of this present research is to determine empirical prediction equations based upon experimental conditions relevant to the real world. A secondary purpose of this presentation is to examine the differences noted in the various prediction equations (Nickerson, 1958). It is highly likely that the differential predictions arise as a result of the differential experimental procedures employed by the separate investigators. This presentation will note these methodological differences, and attempt to discover what procedural variables influence the obtained results.

In order to develop a set of predictive equations, it is necessary to determine what colors remain the same under the daylight and tungsten illumination conditions, i.e., to identify which colors display "color constancy". The tristimulus values under daylight (source C) and tungsten (source A) can be related by the following sets of equations:

$$\begin{aligned} X' &= a_{11}X + a_{12}Y + a_{13}Z \\ Y' &= a_{21}X + a_{22}Y + a_{23}Z \\ Z' &= a_{31}X + a_{32}Y + a_{33}Z \end{aligned} \qquad \text{(Eq. 1)}$$

or:

$$\begin{aligned} X' &= a_{11}X + a_{12}Y + a_{13}Z + a_{14} \\ Y' &= a_{21}X + a_{22}Y + a_{23}Z + a_{24} \\ Z' &= a_{31}X + a_{32}Y + a_{33}Z + a_{34} \end{aligned} \qquad \text{(Eq. 2)}$$

X', Y', and Z' represent the tristimulus values under one condition, X, Y, and Z represent the tristimulus values under the other condition. the a_{ij}'s are the constants that may be found to relate the daylight and tungsten tristimulus values, if the appropriate primed and unprimed values are known for the constant colors. The experimental task is thus defined: somehow these constant colors must be found.

HISTORY

Several methods have been proposed for determining these constant colors. Helson (1938, 1940, 1943, 1947, 1952) has employed a "memory method". He required observers to memorize the relationships and designations of the Munsell colors. When they reached a satisfactory level of performance, they were requested to name Munsell samples presented under Macbeth Daylight. At a later time, they were given the same samples under tungsten light, and were requested to describe the apparent color in Munsell terminology. The differences between the daylight designation and the tungsten designation described the apparent color shift. Samples that did not shift showed constancy. Judd (with Helson and Warren, 1952) performed an extensive *post hoc* analysis of the data gathered by this method and produced the first predictive equations:

$$X_a = .866X_c + .396Y_c - .124Z_c$$
$$Y_a = 1.0Y_c$$
$$Z_a = .301Z_c \qquad \text{(Eq. 3)}$$

These describe the color change from source C to source A. and show shifts from the blue to the yellow. The amount of color change is dependent upon the initial color of the sample. Blues show the greatest shift while the yellows show the least.

A second experimental method, the "binocular septum technique", has been employed by several authors (Burnham, Evans and Newhall, 1952, 1957, 1959, and Wassef, 1955). The apparatus for this has two separate large field chambers, one which is illuminated with a daylight source, the other with a tungsten source. The observer views one field with the left eye, the other with the right. Within each field is a small ($1^o \times 2^o$) aperture upon which the stimulus lights are projected from behind. Fixation points are provided in each field, on the right side of the sample in the left eye, and on the left side of the right eye sample. When the observer fuses these fixation points, the two stimulus fields appear as one split field. The observer's task is to adjust the variable color patch of light in the left eye to match the standard in the right eye. The critical measure in this method is the difference in the match of a sample in the left eye under tungsten adaptation, and then later under daylight. The subject, through the use of three control knobs, actively adjusts the appearance of the color in the left eye.

Pilot studies indicated that the mere act of looking steadily at a color changed its appearance. They eliminated this by having the standard and sample colors presented only .3 seconds every second. Their results were plotted on the CIE chromaticity diagram in the form of vector shifts. Their general findings (1952) are quoted below:

(1) Change from adaptation to tungsten light to adaptation to daylight resulted in a substantial correlative shift in perceived color toward the yellows. Similarly, change from daylight to tungsten adaptation produced similar shift towards the blues....

(2) The amount of the chromaticness shift varied with the test colors and other factors, but it was

of the order of some 20 just perceptible differences.... (p. 605).

In general, their results were the same as Helson's.

Burnham, Newhall and Evans made no predictive equations from this data. However, Brewer (1954), using Burnham, Evans and Newhall's data, did produce a set of transformations. The mathematical method he proposed is a 9-constant least squares solution to three simultaneous equations. The nine a_{ij} coefficients shown in Eq. 1 are derived from appropriate multiplication and summing of the primed and unprimed tristimulus values representing visual invariance. The derivation and example calculations for the method are given in his 1954 article.

In 1957, Burnham, Newhall and Evans replicated their prior research, using daylight, tungsten and a green source. Their results were the same. However, they analyzed their data in greater depth, and applied a slightly modified form of the Brewer method to their data. Equation 4 presents their results:

$$X_a = .9132X_c + .422Y_c - .1988Z_c + .0024$$
$$Y_a = .0299X_c + 1.0215Y_c - .102Z_c + .0025$$
$$Z_a = .0175X_c - .1387Y_c + .4708Z_c - .0019 \quad \text{(Eq. 4)}$$

These are 12-constant predictions, and are of the same style as shown in Eq. 2.

Wassef (1955), working independently of Burnham, Evans and Newhall, did an investigation of the same type. She used a binocular matching task, having the eyes differentially adapted, and had the observers select Munsell samples that matched under these two conditions. This is actually a short term memory method; the observers were permitted to view only one sample at a time with either eye.

While Wassef produced no mathematical description of her results, Burnham (1959) examined her data in comparison to his earlier work. Wassef provided enough data for Burnham to made prediction equations, and he showed that with the exception of some minor differences, both the B-E-N equations and the Wassef equations were producing the same results.

At this point, some differences in experimental procedures should be noted. The previous research attempts have differed in the amount of chromatic adaptation permitted, in the type of colors presented to the observers, and in the viewing conditions. All of the studies required that the observer become adapted to the illumination conditions of the viewing situation for several minutes prior to making any judgments. Burnham, Evans and Newhall's conditions were slightly stricter than those of Helson; the colors were presented for only a short time so that the illuminant conditions were maximally effective in causing adaptation. Burnham, Evans and Newhall employed "aperture" or "film" colors (mixtures of lights), while Wassef and Helson used real samples (Munsell chips). Finally, it should be noted that only Helson's observers were in a real world viewing situation, having both eyes adapted in the same way to the illuminant. The other studies employed differential adaptation of the left and right eyes. Table 1 presents a breakdown of these differences in methodology.

TABLE 1

A breakdown of the differences in methodologies employed by the various experimenters.

Investigator	Degree of Adaptation	Stimuli used	Method of Presentation
Burnham, Evans and Newhall	Total	Aperture	Septum
Wassef	Total	Munsell samples	Septum
Judd-Helson	Fairly complete	Munsell samples	Binocular

METHOD

Observers:

Seven professional colormatchers participated in this research. Since these men are accustomed to judging color swatches daily, it was thought that they would be more consistent between and within themselves than non-professional observers. Furthermore, these colormatchers have a language that shows the necessary three dimensions of a color space, and are able to give descriptive adjectives of color shifts due to their long practice in color judgment. The age of the observers ranged from 35 to 59 and their years of experience ranged from 13 to 39 years.

Apparatus:

The stimuli used in this research consisted of 264 samples of Creslan carpet material, dyed with mixtures of American Cyanamid acrilic dyes. The samples measured two by three inches and consisted of a tight weave fabric, about one quarter of an inch thick. The samples were arranged in "batches", each batch containing a number of samples that were intended to appear the same under CIE source C. Initially, 26 batches were planned, representing five major hues and the neutrals of Munsell space at three levels of value and low and high levels of chroma, if possible. Due to the fact that certain high chroma colors could not be made with the available dyes, only 18 batches were finally prepared for the present experiment. The Munsell designation of each batch and the final number of samples in each batch appear in Table 2 and still appear to represent color space well.

TABLE 2

Munsell designations of the 18 batches constructed, and the actual number of samples in each batch.

1.	5R	2/6	19
2.	5R	5/6	19
3.	5R	5/14	3
4.	5R	8/2	18
5.	5Y	5/4	19
6.	5Y	5/8	22
7.	5Y	8/6	12
8.	5G	5/4	17
9.	5G	5/8	9
10.	5G	8/2	8
11.	5B	2/4	14
12.	5B	5/4	15
13.	5B	5/8	10
14.	5PB	2/8	6
15.	5PB	5/4	18
16.	N	2/	22
17.	N	5/	21
18.	N	8/	12

The samples within a given batch were constructed to satisfy two criteria: they should match each other as well as possible under source C, and be as different as possible under source A. This can be done theoretically by computing all the matches to a Munsell chip that would be possible with a given set of dyes. Since all of these possibilities are tristimulus matches for source C by definition, their chromaticity coordinates under source A can be examined for change characteristics. This permits an initial assessment of how the stimuli are distributed, and permits elimination of dyings that give duplicate points in source A space, thus reducing the number of dyings required.

This process was done mathematically. The reflectance (R) values at sixteen wavelengths of each of the 26 Munsell chips were computed from the K/S values given in the Data for use with Munsell Color Book. Computer colormatching programs (Allen, 1965) have been written that permit the calculation of the concentrations of specific dyes required to match a given sample. The program used in this research examined the sixteen R values of a chosen Munsell chip, and computed all possible tristimulus matches that could be made taking ten basic industrial colorants three at a time. In short, it is a method that provides a number of possible matches that would each be made from different colorants, would have different spectrophotometric curves, and thus have different color properties under source A. The resultant matches given by the computer colormatching program were examined using the above criteria, and samples were selected that spread the maximum amount in source A, matched as well as possible in source C, and avoided redundancy within a given batch. These samples were prepared by the American Cyanamid Company at Bound Brook, New Jersey.

Each sample was then measured on the IDL Signature Model Color Eye, using the abridged spectrophotometric filters at sixteen wavelengths. All measurements were made against a barium sulfate standard. The reflectance curves thus given were then integrated for the four light sources considered in this experiment: source C, source A, Macbeth-7500, and Macbeth-2300. Computed along with these sets of tristimulus values were chromaticity coordinates, and Adams L, a, and b coordinates for Adams Chromatic Value diagram.

Samples were viewed under the tungsten and daylight provided by the Macbeth Industrial illumination booth. Macbeth Daylight is a filtered approximation to natural daylight, and has a correlated color temperature of 7500° Kelvin. The Macbeth Tungsten is a slightly exaggerated representation of CIE source A, with a correlated color temperature of 2300°K. Although these approximations were used in the viewing situation, the computational energy integrations were performed for the four sources, C, A, M-7500 and M-2300, considering each one mathematically distinct, and thus permitting statements about sources A and C, given data from M-7500 and M-2300.

Each of the professional observers viewed the samples under the illumination provided by his own Macbeth booth in his own laboratory. It was assumed for this experiment that all of the factory calibrated booths were the same. This is a reasonable assumption; if the illumination given by these booths varied between color laboratories, the color industry would not rely on them.

Procedure:

The observer was handed a sample and told to report the direction and degree of color shift as he changed the illumination from M-7500 to M-2300. The responses of the observer were recorded in the actual three dimensional language used by the colormatcher in his usual job situation. He would first name a hue shift, then qualify it with an adjective, then give a brightness shift with an adjective, and similarly report on shifts in strength. These dimensions have been discussed by Davidson (1951); it is sufficient to state that these dimensions are independent as far as the colormatcher is concerned, and adequately characterize the sample shift.

Little restriction was placed on the task. The observers were free to feel the samples, hold them close to the light, turn them at various angles, and use any viewing techniques that they customarily employed. The samples were presented one at a time from a given batch, and the observers were permitted a rest between batches. There was no limit on the number of times they were to shift the light sources, and the entire experiment was subject paced. The only task restrictions were that the observers view only one sample at a time, and they were not permitted to go back and review or change a prior decision.

The experiment was designed to be run with no experimenter present, although he was there for most of the trials to observe and record data. As the trials progressed, the experimenter' discussed the ordering of the adjectives and the definitions of the dimensions used. A mutual understanding of these responses was necessary for the data analysis.

Analysis:

The rationale of the data analysis can best be justified by keeping in mind the fact that the central aim of this research is to discover invariant samples. The invariant or useful data point in a given batch is that sample which appears to flare the least under the shift from source C to source A. In other words, the analysis must be designed to assess the color differences shown by the observer's ratings.

For one sample, adjective ratings were given to the color change in hue, strength, and brightness dimensions. Numerical rankings were later assigned to these adjectives so that a "no change" rating was given a rank of "0", "very slight" assigned a "1", "slight" received a "2", and "considerable" shift was ranked "3". The relative ranks assigned were mutually determined by the experimenter and observer as mentioned earlier. These rankings became the primary measure of difference from the daylight appearance in a given dimension.

A total measure of difference in an orthogonal N-dimensional space can be represented by a vector that is constructed from the N components. This forms the basis for all color difference formulas in three dimensional space. It is, therefore, reasonable that a vector could be constructed from the ranked rating in the form of:

$$V = (H^2 + S^2 + B^2)^{\frac{1}{2}} \qquad \text{(Eq. 5)}$$

where V is an indication of the total color difference of the given sample based upon the hue shift, strength shift, and brightness shift. In short, the three responses to each sample given by each colormatcher were assumed to be orthogonal components of a vector that describe a color difference in the dyer's color space.

For a given batch of samples that matched in source C, the vector lengths were determined for every sample in the batch for each of the seven observers. The vectors were then ranked within each subject, with the shortest vector getting the lowest rank and the longest getting the highest rank. Summing across the observers gave marginal totals that reflected the shortest vector for the group. Collapsing across the ranks also normalized the data, discounting constant differences in sensitivity or response criterion between observers. Had all observers agreed exactly in their ranking, the marginal sums would have been simply seven times any individual's ranking for a given sample. If the observers disagreed completely, the marginal sums should have all equaled the mean of the ranks. This second hypothesis was tested using the non-parametric Friedman Two Way Analysis of

Variance. In this application, the Friedman functions in the same manner as the significance test of the Kendall Analysis of Concordance. However, the Friedman does not lose power with tied ranks, as does Kendall's analysis.

RESULTS

The Friedman Analysis indicated that in 8 of the 18 batches, the observers agreed significantly as to how the samples should be differentiated. These significant batches (Batches 1, 2, 5, 6, 7, 15, 16, and 17) provided the data from which predictive equations could be generated. The other 10 batches were deleted from the study at this point. No invariant samples could be selected on the basis of the colormatchers' reports. The lack of agreement also suggests that these batches never had an appropriate (constant) stimulus.

For the batches that were retained, the samples that received the lowest ratings by the observers were chosen as the invariant or constant stimuli. The observers were seldom unanimous in their choice of the "best" sample, but did consistently select samples that were in the same general area of color space. Since the source A and source C tristimulus values of these invariant samples had been previously determined, it was only necessary to substitute these primed and unprimed values into the appropriate equations to determine new prediction equations based on the present data. Both the 9-constant derivation used by Brewer and the 12-constant method proposed by Burnham, Newhall and Evans were employed. The resultant equations summarizing the present experimental finding are presented below for the 9- and 12-constant cases:

$$X_a = 1.78X_c - .4182Y_c - .179Z_c$$
$$Y_a = .4346X_c - .6866Y_c - .0937Z_c$$
$$Z_a = -.0002X_c - .0109Y_c + .2936Z_c \quad \text{(eq. 6)}$$

and:

$$X_a = 1.7594X_c - .3991Y_c - .1826Z_c + .0861$$
$$Y_a = .4268X_c + .6939Y_c - .0950Z_c + .0327$$
$$Z_a = .0012X_c + .0096Y_c + .2938Z_c - .0058 \quad \text{(Eq. 7)}$$

Both predictions state the same results, but the 12-constant equations are more precise.

Figures 1, 2, and 3 display the results of these 12-constant predictions. Also presented in these figures are the predictions given by the B-E-N equations, and the Judd-Helson equations. Wassef's and Brewer's predictions have not been included, as they are considered equivalent to the B-E-N predictions. The circled points in Figure 1 represent the source C appearance of 7 Munsell hues at medium chroma levels and at 8/ value level. The ventors originating at these source C appearance points extend to the appearance predicted in source A. The predicted shifts of the B-E-N equations are signified with a "B"; the Judd-Helson equations with a "J"; the predictions given by this present research are designated by a "P". Figures 2 and 3 are similar displays of the same Munsell hues and chromas, but at 5/ and 2/ value. All figures are plotted on Adams Chromatic Value diagram with a scale that encompasses most of color space. Adams Chromatic Value space has been used in these figures because it corrects coordinates of colors viewed under different illuminations by the tristimulus values of these illuminants. These vectors in Adams Chromatic Value space thus indicate the degree to which the prediction equations differ from the

FIGURE 1

Vectors in Adams Chromatic Value Space produced by the application of the present predictions (P), the Burnham, Evans and Newhall predictions (B), and the Judd-Helson predictions (J) for seven Munsell samples of /8 Value.

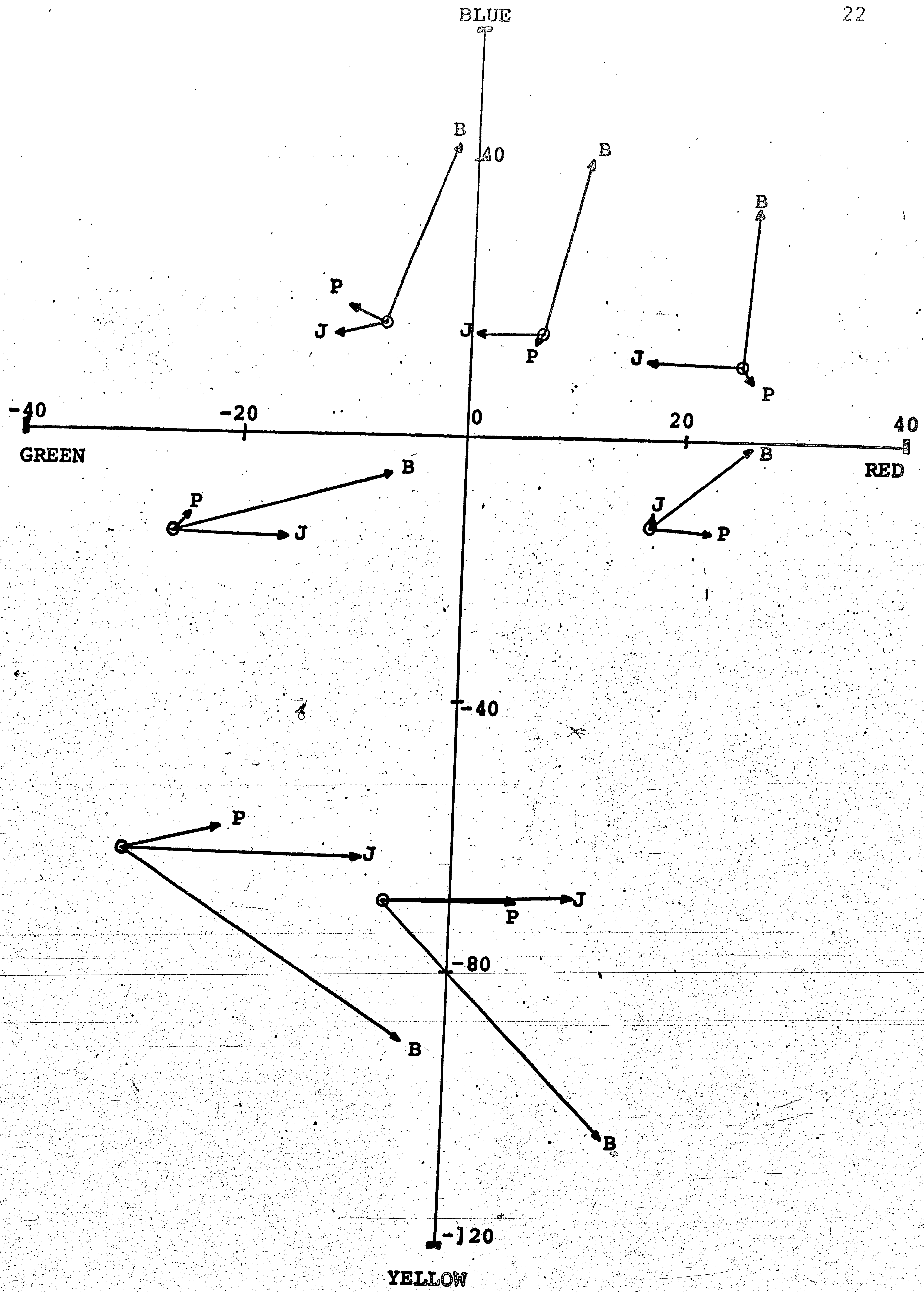

BLUE
40
0
-40
-80
-120
YELLOW
-40
-20
20
40
GREEN
RED
B
P
J

FIGURE 2

Vectors in Adams Chromatic Value Space produced by the application of the present predictions (P), the Burnham, Evans and Newhall predictions (B), and the Judd-Helson predictions (J) for seven Munsell samples of /5 Value.

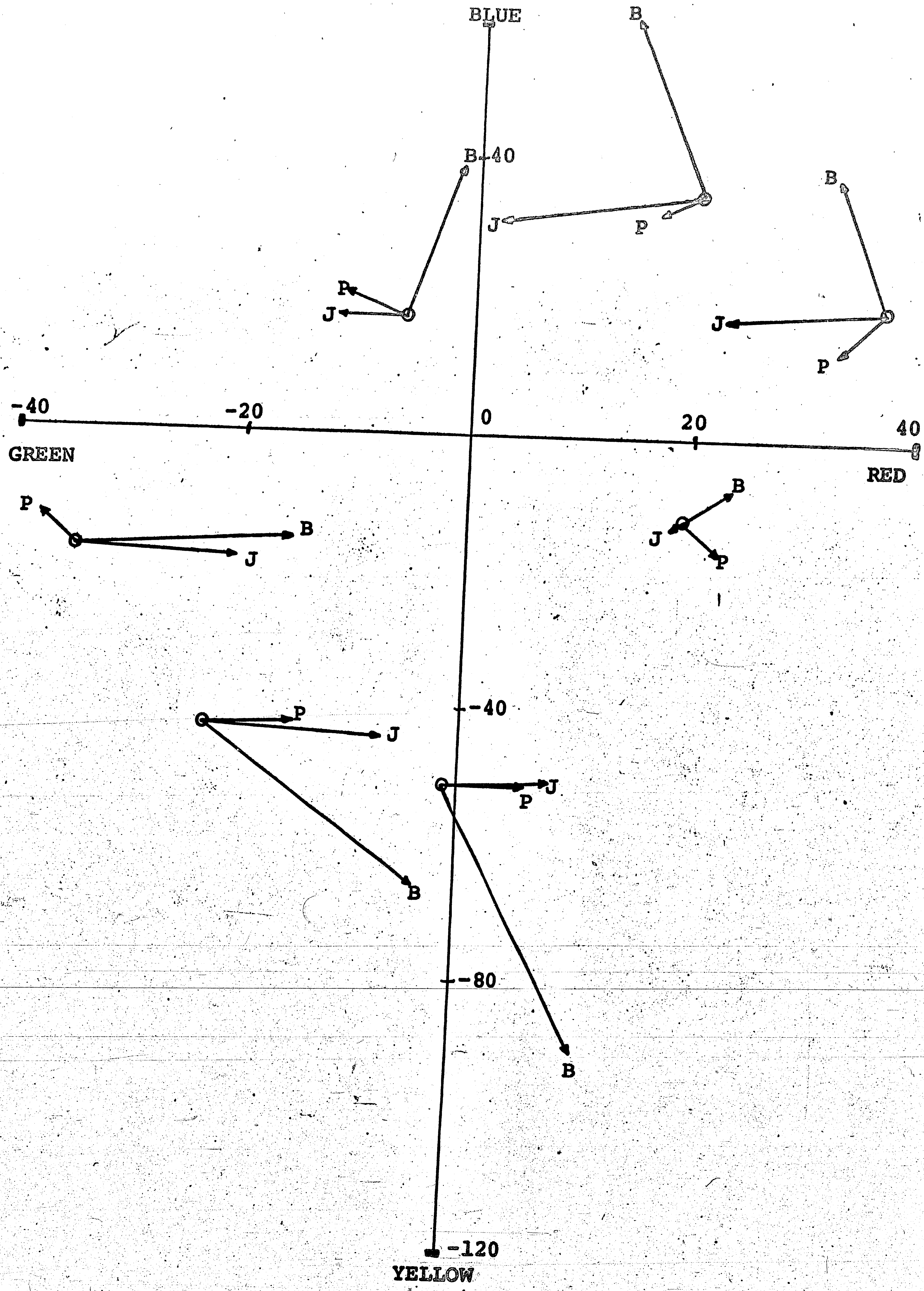
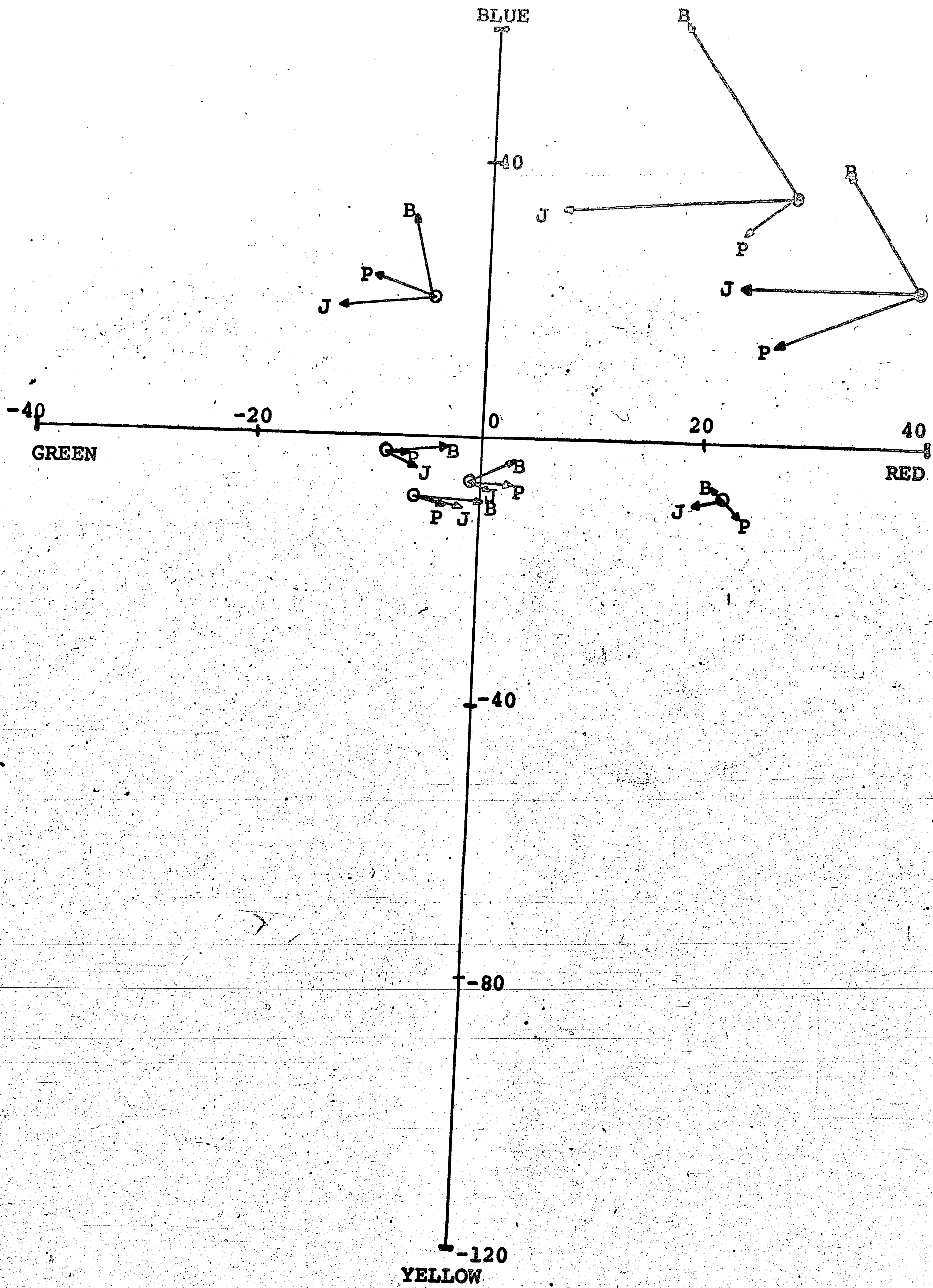

BLUE
40
B
J
P
B
J
P
B
P
J
-40
-20
0
20
40
GREEN
RED
P
B
J
B
J
P
-40
P
J
B
J
P
B
-80
-120
YELLOW

FIGURE 3

Vectors in Adams Chromatic Value Space produced by the application of the present predictions (P), the Burnham, Evans and Newhall predictions (B), and the Judd-Helson predictions (J) for seven Munsell samples of /2 Value.


BLUE
40
-40
-80
-120
YELLOW
-40
-20
0
20
40
GREEN
RED
B
J
P

empirical transform given by the source C and source A tristimulus values.

From these figures, several observations may be noted:

(1) The present predictions are close to the empirical CIE tristimulus value predictions in all areas of color space.

(2) The Judd-Helson vectors are, in general, closer in agreement in terms of vector length to the present results than to the B-E-N predictions.

(3) The B-E-N predictions give in all cases the longest vector differences.

(4) The vectors tend to increase in length as the value level increases from 2/ to 8/.

(5) No definitive conclusions may be made on the differences in vector direction.

All indications point to the fact that the Judd-Helson predictions give results closer to the present predictions than do the B-E-N equations. It may be noted that, with only two exceptions, the (x,y) distance between any Judd and present prediction is less than the (x,y) distance between any present prediction and corresponding B-E-N prediction. This observation was supported by a sum of squares analysis that examined the B-E-N and Judd predicted points relative to the currently obtained data.

DISCUSSION

The analyses demonstrate that there is a marked coincidence between the present study and past research, in spite of the fact that the present procedure represents a departure from the traditional methods. This coincidence may be viewed in opposite ways. It is gratifying to note that the "artificial" situation used in the B-E-N and Helson studies agrees with empirical data. On the other hand, this data may be taken to show how well the colormatchers, in their "artificial" viewing situation of rapidly changing illuminants agree with the data gathered by more controlled scientific methods. While differential predictions do exist, the discrepancies between them are not as significant as they seem.

However, the differences that do arise from these predictions are also interesting. As noted in the introduction, these differential predictions might be expected since the various experimental procedures were different. The basic methodological differences have been noted and summarized in Table 1. Wassef (1955) is included in this methodological comparison since, while her equations showed agreement with Burnham, Evans and Newhall, she employed a slightly different technique. In terms of the distinctions mentioned in Table 1, the present research uses very incomplete adaptation, real samples, and a normal binocular viewing situation.

It was initially supposed that major differences in predictions would develop because of differential degrees of adaptation. However, Observation 2 indicates that this is not the case; the Judd-Helson vector lengths agree well with the present data. If degree of adaptation produced differential results, Helson would be expected to agree better with Burnham, Evans and Newhall, since they used almost complete adaptation to the viewing source.

If it is thus assumed that the vector lengths are not affected by the adaptation state, then possibly the differences between real samples and aperture colors may be producing these magnitude effects. It has been realized since the research of Feldman and Weld (1935) that constancies operate more strongly on real colors than on aperture or film colors. However, Wassef employed real samples, Munsell chips, and produced results similar to those of Burnham, Evans, and Newhall. Table 1 indicates that Wassef's research procedure is compatible in all other respects with the Burnham, Newhall and Evans study, and thus indicates that the real vs. film colors distinction is not critical in differentiating the past and present results.

Considering Table 1 again, it seems that the only apparent differences in methodology that remain unaccounted for are those dealing with the modes of adaptation. It is reasonable to assume that the distinction between differential adaptation and binocular adaptation may produce the observed difference in color shift predictions. If binocular interaction occurred between the blue adapted and yellow adapted eyes of the B-E-N observer, or if there was color rivalry, there would be a reasonable question as to the soundness of their data. Wassef, in a pilot study, discovered that the state of adaptation of one eye had an effect on the other eye; although she decided that the effect was minimal, it was significant at a few wavelengths. Aguilar and Solis (1951) have produced similar results. It is known that interaction does occur in binocular brightness matching if brightness levels are sufficiently different (Sanders, 1968). The question of binocular color mixture is largely unanswered at this time. However, it is suggested that the binocular interaction from these differentially adapted eyes in the septum techniques may be influencing the magnitude of the results, as Figures 1, 2, and 3 show.

The prediction equations resulting from the present research may be considered to be more relevant to the industrial world of colormatching than previous attempts, since the procedure used to gather data on invariant samples was identical to the methods employed in color formulation laboratories. The present predictions may be inserted into any of the present computer colormatching programs to give the colormatcher an opportunity to assess the constancy of a formulation under these daylight-to-tungsten conditions prior to the actual formulation of a dying. In principle, these equations may be viewed as a valuable tool for saving effort on the part of the colormatcher and for improving the quality of dyed products for the consumer.

REFERENCES

Aguilar, M., and M. Solis. Anal. R. Soc. Espan. Fisy. Quim. A, 47, Nos. 11-12, 1951.

Allen, E. "Digital Computer Color Matching". Am. Dyestuff Reptr., 1965, 54, 7-14.

Brewer, W. L. "Fundamental Response Functions and Binocular Color Matching". J. Opt. Soc. Am., 1954, 44, 207-212.

Burnham, R. W. "Predictions of Shifts in Color Appearance with a Change from Daylight to Tungsten Adaptation". J. Opt. Soc. Am., 1959, 49, 254-263.

Burnham, R. W., S. M. Newhall, and R. M. Evans. "Influence on Color Perception of Adaptation to Illumination". J. Opt. Soc. Am., 1952, 42, 597-605.

Burnham, R. W., S. M. Newhall, and R. W. Evans. "Prediction of Color Appearance with Different Adaptation Illuminations". J. Opt. Soc. Am., 1957, 47, 35-42.

Davidson, H. R., and I. H. Godlove. "Application of the Automatic Tristimulus Integrator to Textile Mill Practice". Am. Dyestuff Reptr., 1950, 39, 78-84.

Feldman, S., and H. P. Weld. Perceiving. Chapter 12 in E. G. Boring, H. S. Langfeld, and H. P. Weld (Eds), Psychology. New York: Wiley, 1935, 274-299.

Helson, H. "Fundamental Problems in Color Vision. I. The Principle Governing Changes in Hue, Saturation, and Lightness of Non-selective Samples in Chromatic Illumination". J. Exp. Psychol., 1938, 23, 439-476.

Helson, H. and V. Jeffers. "Fundamental Problems in Color Vision. II. Hue, Lightness, and Saturation of Selective Samples in Chromatic Illumination". J. Exp. Psychol., 1940, 26, 1-27.

Helson, H. "Some Factors and Implications of Color Constancy". J. Opt. Soc. Am., 1943, 33, 555-567.

Helson, H., and J. Grove. "Changes in Hue, Lightness and Saturation of Surface Colors in Passing from Daylight to Incandescent-Lamp Light". J. Opt. Soc. Am., 1947, 37, 387-395.

Helson, H., D. B. Judd, and M. Warren. "Object-Color Chamges from Daylight to Incandescent Filament Illumination". Illum. Eng., 1952, 47, 221-233.

Nickerson, D. "Measurement and Specification of Color Rendition Properties of Light Sources". Illum. Eng. 1958, 53, 77-90.

Saunders, J. E. "Adaptation: Its Effect on Apparent Brightness and Contribution to the Phenomena of Brightness Constancy". Vision Res., 1968, 8, 451-468.

Wassef, E. G. T. "Application of the Binocular Matching Method to the Study of the Subjective Appearance of Surface Colours". Optica Acta (Paris). 1955, 2, 144-150.

VITA

The author was born on April 24, 1945 in Hampton, Virginia, to Mr. and Mrs. James J. Gallagher. He received a B.A. in Psychology from Randolph-Macon Men's College in Ashland, Virginia in June, 1967. At the present, he is employed by Lehigh University as a research assistant, under the sponsorship of Dr. E. Allen of the Department of Chemistry.